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Silicon Micro/Nanomechanical Device Fabrication Based on Focused Ion Beam Surface Modification and KOH Etching

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Selective Ga⁺ ion implantation and milling by focused ion beam exposure and subsequent wet chemical etching is used to fabricate micro/nanomechanical elements in Si. Freestanding elements with a ≈ 30 nm membrane thickness are made by controlled selective underetching between unexposed and exposed areas. Ultrahigh-frequency cantilever beams have been made with resonances in the tens of MHz range. Using a U-shaped beam cross section, mechanical stiffness could be increased 100-fold, which in turn increased the beam resonance frequency to several hundreds of MHz. The direct-write patterning/milling technique was used to fabricate various arbitrary shapes with vertical sidewalls such as submicrometer-sized containers, cups, and other nanomechanical devices.

1. INTRODUCTION

Miniaturization of mechanical devices is important for scaling the device density and its mechanical properties. For example, a cantilever with high resonance frequency and a low spring constant can only be achieved by reducing its mass. Many prospective parallel sensing systems, such as integrated optoelectronic/photonic devices, high-resolution matrix mirror displays, mechanochemical sensor arrays, and high-resolution data storage systems, require a high density of mechanical elements on a very small area. To achieve this, it is necessary to reduce further the size of the devices that are feasible with today's micro-machining techniques, which is a challenging endeavor from a fabrication point of view.

Recently, a technique using the combination of local surface implantation by Ga⁺ ions using a focused ion beam (FIB) and wet chemical etching has attracted much interest [1-3]. It is well known that a high impurity concentration in Si renders the implanted region relatively immune to subsequent etching with certain chemicals, such as potassium hydroxide (KOH) [4,5]. The advantage of using a FIB is that the ions can be exposed locally by direct-write patterning. Despite the disadvantage of being a serial process, it allows the fabrication of arbitrarily shaped devices down to the nanometer range. Underetched structures

have been fabricated by appropriately oriented patterns [1,3]. Their structural thickness is determined by the penetration depth of the ions, which amounts to typically 30 nm for Ga⁺ ions at an acceleration voltage of 30 kV [2]. Interestingly, when milling a hole into the Si by continued FIB exposure, the remaining sidewalls become equally doped due to back scattered ions and hence become also etch resistant. This makes it possible to fabricate arbitrary three-dimensional elements with vertical extensions, such as sidewalls. In this paper we exploit this fact to improve the mechanical stability of ultrathin beams by milling a U-shaped cross section with an increased moment of inertia.

2. FABRICATION

2.1. Focused Ion Beam Patterning and Milling

We use (100) oriented Si wafers with a 10 Ω -cm *n*-type background doping. The FIB system [6] is operated at 30 kV ion beam acceleration voltage with currents in the range of 12-150 pA that are suitable for our purposes in terms of beam resolution, dose, and write time. An advantage of the FIB lies in the nature of the process itself because the direct-write patterning simultaneously creates the mask layer, i.e. no intermediate mask pattern transfer step is necessary. The minimum

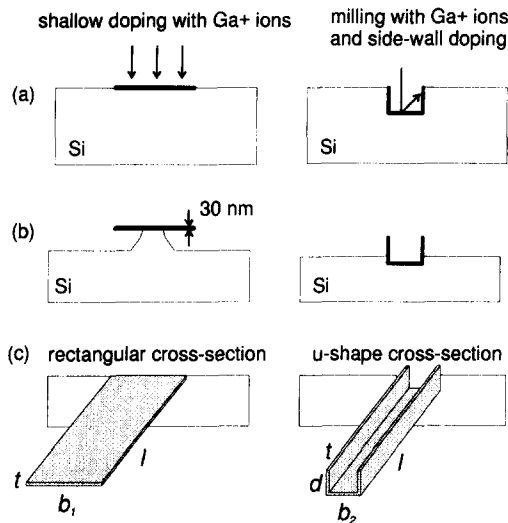


Figure 1. Fabrication of freestanding nanomechanical elements by shallow doping (left) or milling and sidewall doping (right) in various fabrication stages; (a) after FIB exposure, (b) during KOH etching and (c) when etching is completed.

dose required to render an area effectively insoluble in KOH is 10^{15} ions/cm² [1]. For example, a $5 \times 5 \mu\text{m}^2$ area exposed to a current of 100 pA requires only a few seconds to reach the level for the onset of the etch stop.

Material exposed to FIB is simultaneously removed, hence a continued exposure results in a pronounced material removal in this area (for 100 pA we achieve a removal rate of the order of $0.25 \mu\text{m}/\text{min}$). Figure 1 shows schematically the basic patterning procedures for both the shallow doping and the milling approach.

2.2. Wet Chemical Etching

The exposed samples are etched in a 40% aqueous KOH solution at 60°C . This anisotropic etchant has an etch rate on the (100) Si crystal plane of about $0.25 \mu\text{m}/\text{min}$. Alternatively, for very small elements, a slower etch rate for precise time control is preferable and hence we use KOH at room temperature with an etch rate of only $\approx 1 \mu\text{m}/\text{h}$. Freestanding beams are achieved by appropriately orienting the FIB pattern at 45° with respect to the (110) Si crystal plane.

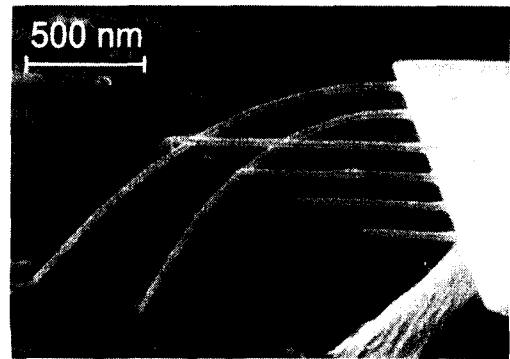


Figure 2. SEM of a series of 30 nm thin and 100 nm wide Si cantilevers with length ranging from $0.5 - 2 \mu\text{m}$. Only the shorter beams are stable enough to withstand the surface tension during the rinsing process.

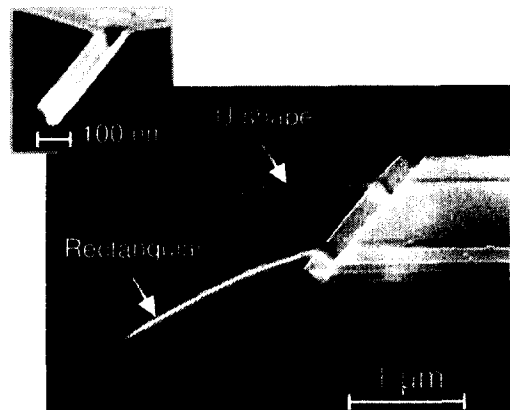


Figure 3. SEM of two 30 nm thin cantilevers with same length and mass, with rectangular and U-shaped cross section demonstrating the stabilizing effect by increasing the moment of inertia.

3. NANOMECHANICAL ELEMENTS

3.1. Ultrahigh Frequency Cantilevers

Using the technique described here, we have routinely fabricated freestanding Si beams with a thickness of 30 nm and a length and width ranging from $0.5 - 10 \mu\text{m}$ and $0.1 - 1 \mu\text{m}$, respectively. Fig. 2 shows a scanning electron micro-

Table 1

Mechanical characteristics of two cantilever beams with a plane vs. a U-shaped cross section. Dimensions: $t = 30$ nm, $b_1 = 100$ nm, $d = 10$ nm, $b_2 = b_1 - 2d = 80$ nm, $l = 1$ μ m, as denoted in Fig. 1.

	plane shape	U-shape	ratio ^a
mass m [kg]	6.9^{-18}	6.9^{-18}	1
moment of inertia I [m ⁴]	2.25^{-31}	2.7^{-29}	120
spring constant k [N/m] ^b	0.11	13.7	120
resonance frequency f [MHz]	20	224	11

^aU-shape vs. normal shape ratio

^bcalculated using the elastic module $E = 1.7 \times 10^{11}$ N/m²

graph (SEM) of a series of 100 nm wide cantilevers. The beams longer than 1.2 μ could not withstand the surface tension forces during the wet rinsing process. The picture shows clearly how fragile the ultrathin elements are. For the nano-engineering of devices with a higher complexity, this weak point can be circumvented as described in the following.

Usually the FIB is used to dope a shallow surface layer. This defines the cross section of the underetched beam to be a rectangular shape (cf. left column of Fig. 1). However, using the FIB to mill a groove results in a U-shape cross section after the KOH with a much higher moment of inertia I of the beam (cf. right column of Fig. 1) which plays an important role in the stability of the ultrathin cantilevers. Referring to the notation in Fig. 1, we can give the moment I of a rectangular cross section as $I_R = (b_1 t^3)/12$, whereas for a U-shaped cross section due to the vertical sidewalls, this moment increases by several orders of magnitude, and can be expressed by [7]

$$I_U = \frac{b_2}{3}(d+t)^3 - \frac{d^3}{3}(b_2 - 2t) - A(d+t-y)^2, \quad (1)$$

where $A = tb_2 + 2td$ and

$$y = \frac{b_2 t^2 + 2td(2t+d)}{2(tb_2 + 2td)}. \quad (2)$$

With increasing I , the spring constant k of a cantilever of length l and an elastic module E , given by $k = 3EI/l^3$, is increased by the same amount. The resonance frequency is given by $f = (1/2\pi)\sqrt{k/m}$. For example, a rectangular cantilever having a length, width, and thickness

of 1 μ m, 100 nm, and 30 nm, respectively, results in a spring constant of $k_R = 0.11$ N/m and $f_R = 20$ MHz, whereas a U-shaped cantilever with same length and mass yields $k_U = 13.7$ N/m and $f_U = 224$ MHz, which is 120 and 11 times higher, respectively. Table 1 summarizes this result.

Figure 3 illustrates the mechanical stabilizing effect of a U-shaped cantilever cross section compared to a rectangular shape. It shows a SEM of two cantilevers with the same length and mass. The ultrathin cantilever with the rectangular cross section cannot withstand the surface attractive forces and is bent down. These forces probably originate from the surface tension during the rinsing process, which, in contrast, the 100-fold stiffer beam can withstand.

3.2. Nanocups and Containers

By extending the vertical FIB milling to several micrometers, real three-dimensional devices with vertical sidewalls of 30 nm thickness can be fabricated. Nanocups with ultrasmall volumes of $\approx 3 \times 10^{-8}$ nl have been fabricated by spot-mode milling a hole 200 nm in diameter and a few micrometers deep. Subsequent etching of the surrounding material leaves very stable elements that can also serve as anchor points for smaller elements such as cantilevers. Figure 4 shows a sequence of SEM images of this process at various stages.

3.3. Nanomechanical Engineering of Complex Structures

By combining the arbitrary pattern/milling of direct-write FIB exposure and anisotropic KOH etching, complex devices can be built. Figure 5

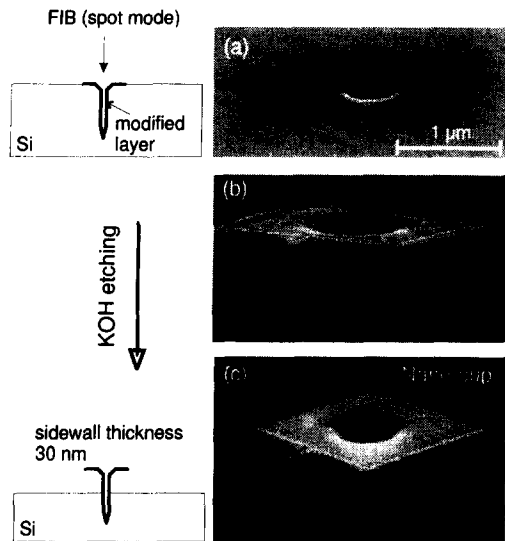


Figure 4. Process sequence for a nanocup (a) after FIB milling a hole in spot mode and shallow area exposure, (b) after 10 min, and (c) after 15 min KOH etching.



Figure 5. SEM of a ultrasmall torsional micromirror fabricated by 3D FIB milling, surface doping and KOH etching.

shows a SEM of a ultrasmall mirror element, where a $2 \times 2 \mu\text{m}^2$ plate is suspended via two torsional hinges to a frame supported by four posts. This element could be used as a pixel in a deflection mirror matrix display with ultrahigh switch-

ing speed. It shows nicely the feasibility of arbitrarily shaped three-dimensional devices by combined FIB/KOH fabrication.

4. CONCLUSION

In summary, we have shown novel micro/nano-mechanical elements fabricated by a combination of FIB patterning/milling and KOH etching, such as cantilevers, cups, and more complex structures. We were able to improve the stability of the ultrathin elements by a factor of over 100 by using the FIB milling to shape a cross section with increased moment of inertia, which in turn results in mechanical resonance frequencies in the hundreds of MHz range.

Truly three-dimensional devices are feasible with the technique presented here. We believe that the presented approach has the potential to become a key process in the fabrication of mechanical systems in the nanometer range.

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